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IMPROVING ARTERIAL MATERIAL CHARACTERIZATION BY INCLUDING DEPOSITION STRETCHES

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SUMMARY

Residual strains in the arterial wall bring extra challenges to the mechanical characterization of arterial tissue. This is due to the complex stress-state of the tissue sample at the beginning of a mechanical test, which is currently most often neglected. A method is suggested to estimate material parameters while taking into account residual strains. Deposition stretches of collagen and elastin are introduced into the Gasser-Ogden-Holzapfel constitutive model. This model is then used in an iterative process, alternating between a finite element simulation to find the elastin deposition stretches and a parameter fitting procedure. Convergence of this iterative process should lead to more reliable material parameters.

Key words: *planar biaxial testing, constitutive modeling, residual stresses, arterial tissue*

1 INTRODUCTION

Arterial tissue is continuously subjected to remodeling, for example during development, renewing of the tissue or after a lesion. The different constituents of the tissue react differently in these remodeling processes and the remodeling must take place in the confined geometry of the arterial wall. The result is that these processes bring mechanical changes into the arterial wall in the form of residual strains. This means the arterial wall is not only stressed by the arterial pressure, but also by internal residual stresses. Therefore, not all stresses in the material can be released by externally unloading the artery. This brings extra challenges regarding the mechanical characterization of arterial tissue.

The characterization of arterial tissue can, for example, be done by performing a planar biaxial test. Material parameters can then be fitted to the experimental data. Generally, the test sample is considered to be stress-free at the beginning of the test. In reality, however, the material is subjected to the aforementioned residual stresses and it is flattened before mounting into the test set-up. Therefore, the assumption that it is initially stress-free might be inaccurate.

It is commonly accepted that a stress-free reference configuration of the arterial wall can be obtained by making a radial cut through the artery as suggested by Chuong and Fung [1]. However, other studies suggest that extra cuts are needed to relieve the material further [2, 3]. Therefore, it is unclear which stress-free reference configuration must be used to fully characterize the residual stresses. As a solution, Bellini *et al.* use the concept of constituent-specific deposition stretches to model the arterial wall mechanics [4]. This paper focuses on the introduction of elastin and collagen deposition stretches in the material parameter fitting on planar biaxial test data.

2 METHODOLOGY

2.1 Constitutive model

An appropriate material model for arterial tissue is obtained by introducing the deposition stretches into the Gasser-Ogden-Holzapfel (GOH) model [5] analogously to Bellini *et al.* [4]. The material is considered to be incompressible. The matrix component in the model accounts for the elastin contribution in the strain energy density function:

$$W_e = C_{10} \left(I_{1e} - 3 \right). \tag{1}$$

I_{1e} is the first invariant of the right Cauchy-Green strain tensor $\mathbf{C_e}$, which is calculated as

$$\mathbf{F_e} = \mathbf{F}\mathbf{G_e}, \ \mathbf{C_e} = \mathbf{F_e}^T \mathbf{F_e}, \tag{2}$$

where $\mathbf{F_e}$ is the total deformation gradient of elastin, $\mathbf{G_e}$ denotes the deformation due the deposition stretch and $\mathbf{F}$ can be any deformation of the artery.

The collagen contribution for both fiber families to the energy is written as

$$W_c = \sum_i \frac{k_1}{2k_2} \left\{ \exp \left[k_2 \left(\kappa I_{1c} + (1 - 3\kappa) I_{4ci} - 1 \right)^2 \right] - 1 \right\}. \tag{3}$$

Here, I_{1c} is the first invariant of the collagen right Cauchy-Green strain tensor $\mathbf{C_c}$. It is calculated in the same way as I_{1e} using $\mathbf{G_c}$ instead of $\mathbf{G_e}$. I_{4ci} is the fourth invariant of $\mathbf{C_c}$ and depends on α_i, representing the orientation of fiber family i.

Assume $\mathbf{C} = \mathbf{F}^T \mathbf{F}$, then the second Piola-Kirchhoff stress is calculated as

$$\mathbf{S} = 2 \frac{\partial W_e}{\partial \mathbf{C_e}} \frac{\partial \mathbf{C_e}}{\partial \mathbf{C}} + 2 \frac{\partial W_c}{\partial \mathbf{C_c}} \frac{\partial \mathbf{C_c}}{\partial \mathbf{C}}. \tag{4}$$

2.2 Estimation of material parameters

The procedure proposed to determine material parameters from the constitutive model is represented schematically in figure 1. The procedure is iterative and alternates between a parameter fitting to obtain material parameters and a finite element (FE) simulation to determine the elastin deposition stretch.

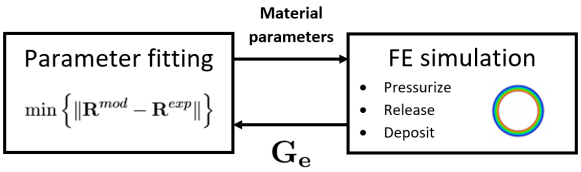

Figure 1: Schematic representation of the iterative procedure alternating between a parameter fitting in which deposition stretches are taken into account and a FE simulation to find the elastin deposition stretch.

The FE simulation is explained in section 2.3. The parameter fitting is done by fitting the material model from section 2.1 to experimental data. The parameters to be fitted are the HGO parameters C_{10}, k_1, k_2, κ and α. Experimental data from planar biaxial tests are used. The fitting is done in MATLAB by minimizing the difference between the measured reaction force at the attachment points and the model force. The model force is the sum of the contribution of different layers, since the elastin deposition stretch is not constant through the thickness of the sample. The model force is calculated as

$$\mathbf{R}^{mod} = \sum_i \mathbf{P}_i A_{0i}, \tag{5}$$

where i denotes the layer number, $\mathbf{P}_i$ is the first Piola-Kirchhoff model stress and A_{0i} is the initial surface of the layer. The objective function to minimize is

$$\|\mathbf{R}^{mod} - \mathbf{R}^{exp}\|, \tag{6}$$

where $\mathbf{R}^{exp}$ denotes the experimentally measured reaction force. The model stress $\mathbf{P}_i$ can be derived as $\mathbf{P} = \mathbf{FS}$ from the second Piola-Kirchhoff stress calculated with equation 4. This equation requires the knowledge of the collagen and elastin deposition stretches. They are determined as explained in section 2.3. Note that the elastin deposition stretch is determined with a FE simulation. However, this simulation needs material parameters. Hence, the iterative procedure shown in figure 1 is developed.

The first step in the procedure is to perform a parameter fitting where the elastin deposition stretch is not taken into account, so $\mathbf{G_e}$ is a unit tensor. Then the simulation as described in section 2.3 is performed with the obtained parameters. The resulting $\mathbf{G_e}$ is then used in the next parameter fitting round. The process alternates further between the simulation and the fitting until convergence is reached, i.e. until the norm of the difference between subsequent elastin deposition stretches is smaller than 10^{-5}.

This procedure is tested on a numerically created dataset of a planar biaxial test.

2.3 Estimation of deposition stretches

For the procedure, the deposition stretches must be known. It is generally assumed that the collagen deposition stretch does not depend on the configuration of the artery because of its high turnover rate [6, 7]. This makes it easy to write the collagen deposition stretch as a deformation gradient $\mathbf{G_c}$ as explained by Cyron *et al.* [8]. However, in this pilot study this deformation gradient is temporarily considered to be unit. The estimation of the elastin deposition stretch is done by assuming that the diastolic configuration is the reference configuration, and that the elastin deposition stretch should balance out the *in vivo* geometry of the artery and the *in vivo* blood pressure [4]. Such an equilibrium is obtained from an iterative FE simulation using the material model explained in section 2.1.

The FE simulation is performed by Abaqus/Standard version 6.14. The *in vivo* diastolic state of an artery is modeled by a hollow cylinder with an outer radius of 3.24 mm and a wall thickness of 0.36 mm with an internal pressure of 11.0 kPa. The length of the cylinder is kept to 1.0 mm and only one fourth of the arc length is used to speed up the simulation. This is reasonable thanks to the axisymmetry of the problem. The mesh is composed of C3D8H elements with an approximate size of 0.09 mm.

The procedure to find elastin deposition stretches repeats three steps (pressurization, release and deposition) until a converged solution is found. The elastin deposition stretch tensor for each element is initially set equal to the identity tensor. In the first step, pressure is smoothly applied to the diastolic geometry. For each element, the resulting deformation gradient is multiplied to the stored elastin deposition stretch tensor. In the second step the pressure is released, such that the material retracts to its unpressurized configuration. In the third step, the deformation obtained at the end of the first step is assigned to the unpressurized diastolic geometry. This way the expansion of the artery decreases between subsequent pressurization steps. The procedure converges when there is no significant deformation anymore during the pressurization step.

3 RESULTS

Figure 2 shows the numerically created dataset in blue. The first Piola-Kirchhoff stresses are given in function of the stretches in two directions. These data are used to test the iterative procedure explained in section 2.2 and shown in figure 1. The procedure reached convergence after four iterations. The result is the model stress shown as a solid red line in figure 2.

4 DISCUSSION

Figure 2 shows a fairly good match between the used dataset and the resulting model after introducing elastin deposition stretches. However, some improvements to the procedure can be made. For example, the parameters κ and α can be verified histologically because they are structural parameters. Hence, it might be a good idea to use fixed values. This way, only three parameters need to be fitted which can lead to a more stable solution. To further improve the procedure, an extra deformation

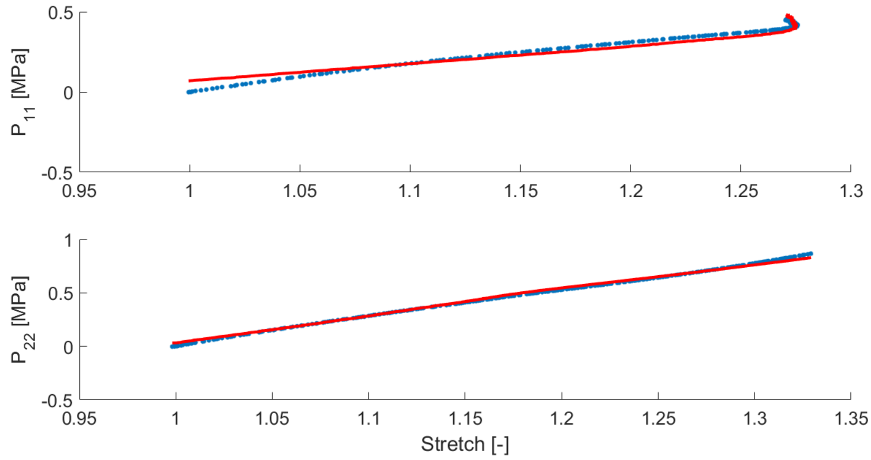

Figure 2: Stress versus stretch curve of the planar biaxial data used to test the procedure (blue dots) and the obtained model after convergence (solid red line). P_{11} and P_{22} are the first Piola-Kirchhoff stresses in the two directions of the planar biaxial test.

should be integrated to account for the recoiling of the artery after a radial cut and the flattening of the test sample. This can be done by multiplying a new deformation gradient to the deformation gradient obtained from the biaxial test. Also, the collagen deposition stretch should be included as explained in section 2.3. The procedure can then be tested on real planar biaxial test data. The method can be adapted to work with pressure-diameter tests. It can then be validated by comparing the material parameters obtained with both methods on the same artery.

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